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ABSTRACT

Recent advances in building energy simulation in North America are reviewed. Six innovative programs — HVACSIM$^+$, GEMS, ENET, TARP, BESA, and BEVA — are described and important new simulation techniques in the areas of functional input, moisture absorption and desorption, interzone airflow, daylighting, and automatic optimization are discussed.

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INTRODUCTION

We present an overview of advances in computerized building energy simulation that have taken place in North America over the last five years (1981-1985)*. During this period the evolution of simulation programs proceeded in two directions. On one hand, there occurred an enormous proliferation of new microprocessor programs based on simplified methods allowing fast, inexpensive analysis of conventional building designs. On the other hand, the trend which began in the late 1970's toward more precise simulation of physical processes continued, resulting in the development of a number of new detailed models and the incorporation of advanced simulation capabilities into existing programs. Space limitations permit an adequate review of only a limited number of these recent activities. Since the simplified methods have been reviewed by Kusuda [1], emphasis will be placed on a selected number of the more "state-of-the-art" developments in the area of detailed, whole-building energy simulation.

The plan of this review is as follows. First, six very different, innovative programs are summarized. Two of them (HVACSIM$^+$ and GEMS) represent major advances in the area of small-timestep simulation of HVAC system dynamics. Next we describe four important advances in specific simulation capabilities: the use of FORTRAN-like input functions to modify simulation algorithms; dynamic simulation of moisture absorption and desorption; calculation of interzone airflow; and daylighting simulation. Finally, some new work in automatic optimization of building parameters is discussed.

NEW SIMULATION PROGRAMS

In this section we review several recently-developed detailed simulation programs. These are HVACSIM$^+$, a variable-timestep, component-based simulation for the study of rapidly-varying system dynamics; GEMS, which is based on the state-space methods of modern control theory; ENET, which uses graph theory to minimize the number of iteration variables for a system and which generates compact customized code for each system configuration; TARP, a research-oriented program which does a simultaneous calculation of thermally coupled zones; BESA, a set of twelve different menu-driven analysis packages tailored to different building professions and different stages of the design process; and BEVA, which allows long-term building performance to be calculated from a few parameters obtained from short-term monitoring.

HVACSIM$^+$: Hierarchical, Variable Timestep Simulation

HVACSIM$^+$ has been developed by the National Bureau of Standards for modelling the short timestep dynamics between a building envelope, HVAC system, and controls [2,3,4]. It is a research-oriented program intended for study of systems whose rapidly-varying dynamics cannot be tracked by hourly analysis techniques. HVACSIM$^+$ uses a hierarchical description and a variable timestepping method which are unique among public domain whole-building programs in North America.

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*This paper has been submitted for publication in a special issue of *Energy and Buildings* devoted to recent developments in building energy simulation. Other articles in this issue will cover simulation advances in Europe, air flow simulation, HVAC systems simulation, control system simulation, model validation, computing options, case studies, and the future of simulation.

A component-based methodology is followed which is based on the TRNSYS [5] program. The simulation procedure is:

(1) a building is decomposed into components (walls, ducts, coils, fans, controls, etc.), each of which is described by a FORTRAN subroutine from a component library; users may add their own subroutines for components not already in the library;

(2) the user assembles an arbitrary system by linking component inputs and outputs and by assigning component performance parameters;

(3) the program solves the resulting set of non-linear algebraic and differential equations to determine the system's response at each timestep.

For computational efficiency, HVACSIM$^+$ uses a hierarchical approach in which components are grouped into *blocks* and blocks into *superblocks*. (The actual breakdown into blocks and superblocks is left to the user.) Each superblock is an independent subsystem: its time evolution is independent of other superblocks. Except for the building envelope calculation, which uses a fixed, user-specified timestep, the timestep in a superblock is variable. It is automatically and continuously adjusted by the program to maintain numerical stability. For example, a sudden change in the value of a boundary variable (such as a set point) causes the simulation timestep in a superblock to be reset to a minimum value.

The program also has a built-in mechanism to "freeze" variables which have reached steady state. Frozen variables are removed from the system of state variables which are solved simultaneously, thus reducing computation time. Frozen variables are then monitored and reinstated into the calculation, or "unfrozen", as soon as the steady-state criterion is no longer satisfied.

HVACSIM$^+$ uses an extension of the Gear algorithm [2] to integrate "stiff" ordinary differential equations (i.e., equations involving a wide range of time constants, a situation commonly encountered in the thermodynamic and control processes which occur in buildings). The procedure is as follows. Let the system of N simultaneous algebraic and differential equations for a superblock be expressed as

$$f_l\,(\bar{x},\dot{\bar{x}},t) = 0, \quad l = 1, \cdots, N \tag{1}$$

where $\bar{x}=(x_1,x_2, \cdots ,x_M)$ is the vector of system state variables, and $\dot{\bar{x}}=(\dot{x}_1,\dot{x}_2, \cdots ,\dot{x}_M)$ is its corresponding vector of time derivatives. A backward differentiation formula expresses $\dot{\bar{x}}(t_n)$, the present value of $\dot{\bar{x}}$, in terms of the present and past timestep values of $\bar{x}$:

$$\dot{\bar{x}}(t_n) \;=\; -\frac{1}{h}\sum_{i=0}^{k} \alpha_i\; \bar{x}(t_{n-i}) \tag{2}$$

Here h is the present timestep size, the α_i are constants, and $1 \leq k \leq 6$. Inserting eqn.(2) into eqn.(1) then gives a system of nonlinear algebraic equations for $\bar{x}(t_n)$, which is solved by a Newton-type iterative method.

An example of the small timestep simulation capabilities of HVACSIM$^+$ is shown in Fig. 1, which compares simulated and measured response of a heating coil to rapid changes in water inlet temperature.

GEMS: State-Space Analysis

The "state-space" approach of modern control theory casts the equations which describe a complex multi-variable system into a special vector-matrix form which is well suited to digital computer calculation. Honeywell has recently developed the proprietary program GEMS (Generalized Engineering Modeling and Simulation) which for the first time embodies state-space methods in a whole-building energy analysis program [6]. In this approach, the coupled algebraic and differential equations which describe the heat and mass flows in a building are cast into the state-space form

$$\dot{\overline{x}} = [A(\overline{x},\overline{u},t)]\overline{x} + [B(\overline{x},\overline{u},t)]\overline{u} \tag{3}$$

$$\overline{r} = [C(\overline{x},\overline{u},t)]\overline{x} + [D(\overline{x},\overline{u},t)]\overline{u} \tag{4}$$

where

$\dot{\overline{x}}$ is a vector (of temperatures, humidity ratios, etc., at various nodes of the system) that describes the state of the system at time t;

$\overline{u}$ is a vector of known inputs (climate variables, control setpoints, etc.);

$\overline{r}$ is a vector of desired response variables (mass flows, zone temperatures, extraction rates, etc).

A, B, C, D are matrices which are determined by the physical characteristics of the system.

The number of equations represented by eqns. (3) and (4) can range from a hundred or so for a single zone, single HVAC system simulation, to a thousand or more for multizone configurations. Therefore, an automated, systematic method is therefore required to cast the building into the state-space form. Once in this form, however, the system of equations becomes amenable to powerful techniques from linear algebra and modern control theory.

In GEMS, system processes are cast into the state-space form by deriving lumped parameter equations at each node from Taylor series expansion or conservation equations. Similarly, the heat transfers in the building structure are transformed to state-space after being expressed in RC network form. Systems described by transfer functions can also be cast into the state-space form. Sparse-matrix techniques and user-selected integration methods are then used to solve the resulting system of equations. Multirate simulation allows stiff systems to be calculated, i.e., smaller integration timesteps can be used for components with rapidly varying dynamics. Since the complexity of the building/HVAC-system network is controlled by the user, GEMS allows a wide range of simulation detail to be handled: from full thermal coupling between zones to simplified, fast-executing models for non-critical components.

Because the state-space approach relies heavily on matrix manipulation, it is ideally suited to computers with array processors designed for fast vector-matrix arithmetic.

ENET: Equation Reduction and Customized Code Generation

The component-based network approach used by programs like TRNSYS and HVACSIM$^+$ results in a large number of simultaneous non-linear equations which are solved iteratively to determine the system state variables at each timestep. In such schemes, the calculation time and stability are very sensitive to the number of variables which are iterated over. A new approach called ENET has been developed by the IBM

Los Angeles Scientific Center which substantially reduces the number of iteration variables for a given network [7]. To illustrate what ENET does, assume that the system of equations at a particular time for a very simple, hypothetical network with four state variables, x_i, is

$$x_1 + x_3 + x_2^2 + x_2^{1/2} = 0 \tag{5}$$

$$x_2 - x_1 \, e^{x_1} = 0 \tag{6}$$

$$x_3 \, x_4 + x_1 \, x_4 + x_4^3 + 1 = 0 \tag{7}$$

$$x_4 - x_3 \, e^{-x_3} = 0 \tag{8}$$

This set would usually be solved by iterating over x_1 through x_4 using a Newton-type algorithm requiring calculation of the 4x4 Jacobian matrix for each iteration. However, by proper matching of equations and variables, eqns. (5) to (8) can be rewritten and reordered as follows, so that one equation is used to solve for each variable:

$$x_2 = x_1 \, e^{x_1} \tag{9}$$

$$x_3 = -(x_1 + x_2^2 + x_2^{1/2}) \tag{10}$$

$$x_4 = x_3 \, e^{-x_3} \tag{11}$$

$$x_1 = -(x_3 + x_4^2 + x_4^{-1}) \tag{12}$$

We see that, if x_1 is given, then x_2, x_3, and x_4 can be determined by successive application of eqns (9), (10), and (11). Thus, the system of equations can be solved by iterating on x_1 alone, and only one Jacobian matrix element (that associated with eqn. (12)) need be calculated.

In ENET, the process of matching variables to equations, as illustrated in eqns. (9) to (12), and then determining a set of iteration variables and a calculation sequence is done automatically using algorithms from graph theory. Moreover, the network of building components and connections is used to automatically generate the underlying graphs for the matching and determination of iteration variables. The resulting equations are then passed to a unique code generator which produces a compact, fast-executing program customized to the network being analyzed. Because the generated code is primarily in-line, run-time overhead of subroutine calls is minimized.

The current version of ENET calculates steady state (time independent) systems only. Extensions to time-varying configurations are under study at Lawrence Berkeley Laboratory.

TARP: Coupled Multizone Analysis

In 1983 the National Bureau of Standards introduced the Thermal Analysis Research Program (TARP) for improved calculation of building loads [8]. TARP is an evolutionary development of BLAST [9]. Although TARP lacks BLAST's equipment simulation, it is easier to modify (and so is adaptable to specific research applications) and contains more detailed models for interzone heat transfer.

Basic to TARP is an hour-by-hour room air heat balance calculation which determines surface temperatures, room air temperatures (assumed uniform throughout each room), and heating/cooling loads. For a room with N surfaces and M openings, the heat balance takes the form:

$$CE + \sum_{i=1}^{N} h_i \, A_i \, (T_i - TZ) + \sum_{j=1}^{M} F_j \, C_p \, (TS_j - TZ) + L = 0 \qquad (13)$$

where

CE = energy convected from internal sources (lights, people, etc.)
A_i = area of surface i
h_i = convection coefficient of surface i
T_i = temperature of surface i
TZ = room air temperature
F_j = mass flow of air through opening j
C_p = specific heat of air
TS_j = temperature of air passing through opening j
L = heat addition from air handling system

The values of surface temperatures, T_i, and room air temperature, TZ, are obtained by an iterative method: (1) TZ is set equal to the previous-hour value; (2) the T_i are found by evaluating a heat balance on every room surface; (3) a better value of TZ is calculated by using these values of T_i in eqn. (13); (4) the T_i are recalculated using the new value of TZ, and so on. The process converges rapidly and can be extended to a simultaneous solution of multiple zones which are thermally coupled by conductive, convective, and radiative heat exchange. The interzone air flow rates, F_j, in eqn. (13) are determined from a multizone flow balance calculation using wind and thermal driving forces. A description of this calculation is given below in the section "Multizone Airflow Analysis".

In the surface heat balance calculation, radiant interchange between room surfaces is based on a network approach in which surfaces interact with a mean radiant temperature instead of directly with each other [10]. This procedure decreases the number of radiant interchange calculations per zone from order N^2 to order N, greatly reducing calculation time and making a simultaneous heat balance for many rooms feasible.

The user may choose between simplified and detailed versions for many of the calculations in TARP, thus allowing a tradeoff between level of input detail, calculation speed and accuracy. For example, incoming direct solar radiation may be assumed to be totally absorbed by the floor; alternatively, the program will geometrically calculate how much of each inside surface is illuminated by sunlight. Other examples are: Solar gain through windows can be found by the ASHRAE shading coefficient method, or by using the solar-optical properties of each pane of glass. Infiltration can be calculated by a simple air-change method or by performing a multizone flow balance. Outside surface temperatures can be determined from an effective surface coefficient or from a detailed calculation of surface convection and long-wave radiant interchange with sky, ground and neighboring buildings.

An illustration of TARP's ability to predict hour-by-hour heating and cooling loads is shown in Fig. 2 [11].

BESA: A New Approach to the User Interface

Under development by Public Works Canada is a new program, BESA (Building Energy Systems Analysis), which consists of twelve packages tailored to the needs of a variety of building professionals at specific stages of the building design process [12]. BESA departs radically from its predecessors, which have tended to be biased toward a particular class of end-user (such as the mechanical engineer) or toward a particular building design consideration (such as HVAC equipment sizing).

The planned BESA packages, which are menu driven and designed to run on personal computers (PC's), are listed in Table 1. Except for package #6, energy calculations are based on ASHRAE's TC 4.7 simplified energy analysis bin method [13] with extensions for monthly calculations and with enhancements to the solar gain and shading analysis. Package #6 is aimed at detailed design by engineers and researchers. It will be a small timestep (less than one hour) TRNSYS-like component-based simulation capable of modelling energy management control systems.

Table 1

BESA Program Packages

Package no.	Design stage	Designed for	Expected completion date
1	Pre-Design	Architect	Feb. 1987
2	Pre-Design	Building Owner/ Property Manager	
3	Concept	Architect	Aug. 1986
4	Concept	Engineer, Researcher	
5	Detail	Engineer, Researcher	Sept. 1988
6	Detail	Engineer, Researcher (small timestep)	
7	Detail	Building Contractor	
8	Commissioning	Commissioning Agent/ Building Contractor	May 1989
9	Retrofit	Architect	Available now
10	Retrofit	Engineer, Researcher	
11	Retrofit (Pre-Audit)	Building Owner/ Property Manager	
12	Retrofit	Project Manager (A/E)	

The first set of modules now publically available is for retrofit analysis (deemed to be of first priority in a nationwide survey of user needs [14]). The retrofit package has several unusual features: (1) To determine if a building is a retrofit candidate, a pre-audit analysis compares a building's past utility bills to an optimum average derived from a database of the same building type. (2) The program will execute any number of up to 50 energy conservation measures in order of least capital cost, and will calculate the incremental savings of each measure. (3) The program will automatically perform parametric analysis by incrementally varying user-selected variables (such as cooling setpoint, roof insulation, glazing area, etc.) and comparing the results with a base case.

The remaining packages are scheduled to be released to the market sector over the next two to three years.

BEVA: Macrodynamic Analysis

The approach used by simulation programs like TARP and HVACSIM$^+$ is *micro*dynamic in the sense that the dynamic performance of a building is calculated from basic equations of heat and mass transfer using a detailed, "micro" description of the physical characteristics of the building and the associated climatic driving forces. There are, however, three basic problems with microdynamic simulation: (1) a first principle calculation almost always involves approximations whose impact is difficult to estimate; (2) the connection between system performance and input variables can be masked by the complexity of the processes involved; and (3) for an existing building it is often impossible to determine the "as-built" input parameters required by the calculation.

To overcome these difficulties, a new, *macro*dynamic technique called Building Element Vector Analysis (BEVA) has been developed by the Solar Energy Research Institute in which short-term measurements on an existing building determine a few characteristic "system parameters" [15,16]. These are then used to predict the long-term hourly behavior of the building. In the BEVA method, detailed input data, such as the layer-by-layer physical properties of the building envelope, are unnecessary. Furthermore, the derived system parameters are directly related to system performance and have a clear physical meaning.

The macrodynamic approach is based on a transfer function representation of building response. For a single zone (the method is extendable to multiple, coupled zones) a heat balance on the zone air at time t can be described by a convolution integral:

$$\int_{-\infty}^{t} dt' \; [V(t-t')T_{in}(t')-W(t-t')T_{out}(t') - S(t-t')Q_{sun}(t')]$$
$$= Q_{int}(t) + Q_{aux}(t) \qquad (14)$$

where T_{in} and T_{out} are inside and outside air temperature, respectively; Q_{int} is internal heat gain; Q_{aux} is auxiliary energy; and Q_{sun} is the incident solar radiation. V and W are transfer functions which describe the response of heat flow from room air due to changes in indoor temperature and outdoor temperature, respectively. The transfer function S gives the heat flow from room air due to solar radiation.

Taking the Fourier transform of eqn. (14) gives

$$V(\omega)T_{in}(\omega) - W(\omega)T_{out}(\omega) - S(\omega)Q_{sun}(\omega) = Q_{int}(\omega) + Q_{aux}(\omega) \qquad (15)$$

In BEVA a least squares regression applied to short-term measurements of room temperature or auxiliary energy are used to determine the system parameters V, W and S at two frequencies: $\omega=0$ (steady state) and $\omega=\omega_D$, the diurnal frequency. Each of these parameters has a simple physical meaning. For example, $V(\omega=0)$ and $W(\omega=0)$ are both equal to the building envelope loss coefficient, and $S(\omega=0)$ is proportional to the average solar gain. Values of V, W and S at other frequencies are obtained by interpolation using a simple RC network representation of the building, with circuit parameters determined by V, W and S at $\omega=0$ and $\omega=\omega_D$.

A sample BEVA analysis is shown in Fig. 3. The S, V and W system parameters for the Los Alamos direct gain test cell were determined from four days of measured performance data. These parameters were then used in eqn. (11) to predict the next six days of performance. The *rms* deviation between measured and predicted inside air temperature over the six days is very small — 0.68 °C — demonstrating the robustness of the approach.

Some applications of BEVA are: (1) retrofit benefits can be assessed via short-term before and after monitoring to determine the BEVA system parameters, from which before and after long-term predictions can be made; (2) occupancy effects can be studied by short-term monitoring with and without occupants; (3) similarly, the solar contribution to a passive solar building can be experimentally determined by short-term monitoring with and without the solar feature; and (4) systems analysis of new products is facilitated by using BEVA to provide a simplified model of the rest of the building.

NEW SIMULATION CAPABILITIES

In this section we review a number of advanced techniques which have been integrated into public-domain simulation programs.

Algorithm Modification Via Input Functions

It often occurs in building energy analysis that the particular simulation technique being used cannot adequately model an innovative building component, system configuration, or control scheme. The analyst is then forced to switch to another program or modify and recompile the program in hand. To avoid the inconveniences associated with these alternatives, a new feature has been incorporated in the DOE-2 program which allows users to modify the DOE-2 algorithms by entering FORTRAN-like functions in the program *input* and specifying where in the hourly calculation sequence the functions are to be evaluated [17]. Most of the internal program variables in DOE-2 can be accessed and/or modified by such input functions via algebraic or logical expressions, just as in FORTRAN. This procedure avoids program recompilation, which usually requires special expertise and can be quite expensive.

The following simple example illustrates an input function to model sun-control glass with a dynamically variable shading coefficient — a situation which could not be handled by previous versions of the program. The shading coefficient of this hypothetical photochromic glazing decreases linearly from 0.9 to 0.3 as the solar radiation striking the window increases from 0 to 200 Btu/ft^2-hr, and stays at 0.3 for higher intensities. The DOE-2 input for this case might look something like:

```
      .
      .
      .
WINDOW        HEIGHT=6
              WIDTH=20
              FUNCTION=(*F-1*,*NONE*) ..
      .
      .
      .
FUNCTION      NAME=F-1
              LEVEL=WINDOW ..

ASSIGN        SHCOEF=GSHACO
              SOLDIF=QDIF
              SOLDIR=QDIR ..

CALCULATE ..
          SOLTOT=SOLDIF+SOLDIR
          IF(SOLTOT.GE.200.) SHCOEF=.3
          IF(SOLTOT.LT.200.) SHCOEF=.9-.6*SOLTOT/200.
          END

END-FUNCTION ..
```

Here GSHACO, QDIF and QDIR are internal program variables equal to shading coefficient, incident diffuse solar radiation intensity and incident direct solar radiation intensity, respectively. The user has assigned SHCOEF, SOLDIF and SOLDIR to be the corresponding variable names local to the function. SOLTOT is another local variable which the function calculates to be the total incident radiation. After SHCOEF is determined by the function, its value automatically becomes the value of GSHACO, which is subsequently used by the window thermal algorithm to determine the solar heat gain through the window.

The function input capability is currently available only in the DOE-2.1C envelope calculation. It will be extended to the HVAC systems calculation in DOE-2.1D.

Moisture Absorption and Desorption Analysis

Absorption and desorption of moisture in room envelope and furnishings has generally been neglected in building thermal analysis because the physical processes involved are very complex. However, moisture storage can have significant effects on the hourly latent load profile. For example, in a moist climate the latent component of a morning pull-down load could well be dominated by the release from room surfaces of water vapor absorbed during the night from infiltration and ventilation air.

To study the dynamic effects of moisture, the Florida Solar Energy Center has developed an approach called MADAM (Moisture Absorption and Desorption Analysis Method [18,19]). Within MADAM, a detailed finite-element code known as FEMALP (Finite Element Methods Applications Language Program) solves the coupled heat and mass transfer conservation and momentum equations in solids and at the solid/air interface [20]. The result is a set of coefficients which determine the rate at which moisture is absorbed and released at interior surfaces. These coefficients are then used in MAD-TARP [18], a special version of the TARP program, to investigate the hourly impact of moisture storage on HVAC system performance and comfort conditions.

For an in-room air conditioner, the room moisture balance equation in MADTARP is

$$m\dot{w}_r = M_{int} - M_{ac} + ACH^*m\,(w_o - w_r) - CON - ABDES$$

where w_r and w_o are the room air and outside air humidity ratios, respectively; m is the dry air mass; M_{int} is the rate of moisture gain from internal sources (occupants, etc); M_{ac} is the moisture removed by the air conditioning unit; ACH is the air change rate due to infiltration and ventilation; CON is the rate of moisture removal by condensation on room surfaces; and ABDES is the net rate of moisture absorption or desorption by the envelope and internal furnishings. This last term is given by

$$ABDES = \sum_{i=1}^{N} h_{m,i} A_{m,i} (w_r - w_{s,i})$$

where $A_{m,i}$ is the effective moisture absorption/desorption area for the ith surface, $h_{m,i}$ is the corresponding convective moisture transfer coefficient, and $w_{s,i}$ is the surface humidity ratio which is characterized in terms of zone air conditions and material surface temperature. The quantities $h_{m,i}$ and $w_{s,i}$ are based on the MADAM preprocessor analysis.

A sample moisture analysis is shown in Fig. 4 which compares room relative humidity values calculated by MADTARP vs. values calculated by the base version of TARP without moisture storage. Widespread application of this kind of analysis is currently inhibited by a lack of measured data on the moisture characteristics of commonly-used building materials.

Multizone Airflow Analysis

An accurate heat balance calculation on a room should include the effects of air movement into and out of the room arising from infiltration of outside air, convection through openings between rooms and, of course, supply air from the HVAC system. Although most simulations account for supply air, and, to varying levels of precision, for infiltration, the effect of air movement between rooms is not accounted for since this requires a simultaneous, coupled multizone solution. Such a solution is, however, beginning to appear in some of the more research-oriented programs. We describe here the approach used in TARP [21]. A similar technique has been incorporated in DEROB [22], and a simplified method based on user-specified interzone air flow rates has been added to BLAST [9].

The flow due to a pressure difference Δp across an opening can be written

$$F = ka(\Delta p)^x$$

where k and x are constants which depend on the nature of the flow restriction and a is a constant which depends on the size of the restriction. For example, orifice flow at high Reynold's number would give

$$F = C\sqrt{2/\rho}\,A\,(\Delta p)^{0.5}$$

where A is the opening area (m^2), ρ is the air density (kg/m^3), and the flow coefficient, C, is 0.6 for a wide range of Reynold's number.

For exterior surfaces, Δp is the difference between the wind pressure and the zone pressure at the centroid of the surface (taking into account the contribution of temperature-induced "stack pressure"). For simple building shapes in exposed conditions, data exist to enable the wind pressure distribution to be estimated as a function of free-stream wind speed and direction. In more complex situations, particularly those where local wind effects are strongly influenced by neighboring buildings or other obstructions, wind tunnel measurements of the exterior pressure distribution may be required.

In TARP, a mass flow balance on each room gives (assuming steady state flow conditions hold during each hour timestep)

$$F_s + \sum_i F_i = 0$$

where F_s is the net mass flow into the zone from the air handling system (supply air minus return and exhaust air) and the F_i are flows through openings in the room's bounding surfaces, including those between adjacent rooms. The mass balances form a set of simultaneous non-linear equations in the room air pressures which are solved iteratively each timestep with a modified Newton's method.

The TARP model also handles airflow through large vertical openings such as doorways. In this case, a temperature difference between rooms causes air flow in one direction at the top of the doorway, and in the opposite direction at the bottom.

Extensions to the air flow model have recently been made [23] to calculate inter-room contaminant movement, thus permitting indoor air quality issues to be investigated in the context of a building's thermal behavior.

Daylighting Simulation

Current interest in daylighting as a way of reducing electricity use and peak demand has stimulated incorporation of daylight illuminance and lighting control calculations in thermal analysis programs. We describe here one of the first such efforts — the integration of daylighting routines into DOE-2 [24].

For computational efficiency the DOE-2 daylighting simulation is divided into two main stages: a preprocessor and an hourly calculation. In the preprocessor, interior daylight illuminance values are calculated at user-selected control points inside the room. The calculation is done for a standard overcast sky and for standard clear skies with 20 different solar altitude and azimuth values covering the annual range of sun positions. Illuminance is determined by sub-dividing each window or skylight into small rectangular elements and finding the luminous flux reaching the control points from each element. The luminous flux from the daylight that is reflected from interior surfaces is also calculated. The net interior illuminance values are then divided by the corresponding exterior horizontal illuminance to yield "daylight factors", which are stored in a library. Analagous "glare factors" are also calculated to allow assessment of discomfort glare from bright windows. The interior illuminance and glare calculation accounts for such variables as the luminance distribution of the sky, ground, and obstructions (such as neighboring buildings); size and orientation of windows and skylights; angle-dependent glass transmittance; inside surface reflectances; and the effect of sun-control devices such as drapes and overhangs.

In the hourly calculation, the illuminance and glare contribution from each window for the prevailing sky conditions is found by interpolating the pre-calculated daylight factors using the current-hour sun position and cloud cover, then multiplying by the current-hour exterior horizontal illuminance. (The interpolation procedure reduces computation time by a factor of 200 compared to hourly re-integration over each window.) At this point, if a glare-control option has been specified, the program will automatically close window blinds or drapes if necessary to decrease glare below a user-specified comfort level. A similar option can be invoked to deploy shading devices for sun control if transmitted solar gain exceeds a threshold value.

The program next simulates stepped or continuously dimming lighting control systems to find the electrical lighting needed to make up the difference, if any, between the daylighting level and the design illuminance setpoint. Finally, the lighting electrical requirements are passed to the thermal loads and HVAC equipment calculation which determines hourly heating, cooling, and lighting energy requirements and costs.

One application of the program is to determine what combination of glass area and transmittance will maximize the cost- or energy-savings benefits of daylighting. An example is given in Fig. 5 which shows DOE-2 predictions for total annual energy use with and without daylighting for an office module in Los Angeles [25].

AUTOMATIC OPTIMIZATION

Current use of computer programs to assess the impact of different design choices on building performance typically involves changing one design parameter at a time and comparing one or more objective functions (such as energy use or life-cycle cost) with a base case. This procedure can be very time consuming and expensive when multiple parameters are considered since the number of simulation runs required increases exponentially with the number of parameters. An alternative is to automate the process by using numerical optimization techniques to minimize the objective function. Such techniques generally require hundreds, or even thousands, of calculations of annual building performance in a single run. However, as computers become faster, numerical optimization is receiving increased attention from the research community.

We describe here the recent work by Carroll in whole-building optimization [26]. Related studies have been done by Byrne in residential optimization [27], Silverman *et al* in optimal HVAC control simulation [28], Jurovics *et al* in optimal building-envelope materials [29], and Addison in multi-criterion optimization [30].

Carroll has developed a method applicable to conduction-dominated buildings that simultaneously optimizes selected building envelope and equipment efficiency parameters, using life-cycle cost as the objective function. The method consists of embedding a fast but accurate simplified energy simulation model (BCEGY) together with a cost estimation algorithm into commercially available general nonlinear optimization software [31].

BCEGY estimates space heating and cooling loads for day and night periods on a monthly basis using a variable-base degree-day method. In addition to the normal features of such models, BCEGY accounts for IR radiation from external surfaces to the sky, window shades, arbitrary thermostat settings for heating and cooling, thermostat deadbands between the heating and cooling setpoints, heating setback and cooling setup, natural ventilation cooling, and the storage and subsequent nighttime release of solar gains in the structure and contents of the house.

The house is treated as a single conditioned zone, with an unconditioned ventilated attic and a perimeter-insulated slab-on-grade floor. A gas or oil furnace and a central air conditioner are simulated to determine monthly and annual purchased utility requirements. The equipment simulations account for part-load performance, fan energy requirements for air distribution, and in the case of the air-conditioner, latent cooling requirements. Appropriate equipment sizing for a particular house configuration is determined from the more stringent of either peak design weather conditions or specified minimum times for temperature recovery from setback or setup. Annual sensible load comparisons between BCEGY and the detailed hourly energy analysis program BLAST indicate agreement to within 5% for heating and 10% for cooling across a wide range of U.S. climates, while BCEGY runs about 1000 times faster than BLAST.

In general, the life-cycle cost objective function is a nonlinear function of its arguments. Its first and second partial derivatives, which are used by the optimization routines, are determined numerically. Aside from range constraints on the optimization parameters that keep them within physically meaningful limits, the optimization itself can either be constrained or unconstrained. The numerical methodology has been developed to allow for either initial-cost or energy-consumption constraints (which are in general nonlinear functions of the optimization parameters).

Figure 6 shows constrained optimal configurations and related building energy performance for a typical residence as a function of incremental first cost relative to a "minimally-performing" building, assuming national average utility costs and New York City weather. It is representative of the results that this numerical building optimization methodology can produce. In this example, eight parameters are being optimized: R-value of wall, floor and ceiling insulation; number of window glazings; south/north window area ratio; infiltration rate; air-conditioner COP; and furnace efficiency. The total computation time to perform all the optimizations for this figure was about 10 minutes on an ELXSI 6400 minicomputer.

CONCLUSION

We have reviewed a number of detailed computer programs and analysis techniques that have advanced the state-of-the-art in building energy performance simulation in North America over the past five years. In the coming years, we expect to see a continuation of the current proliferation of PC-based simplified methods which are making energy analysis easy and affordable. (Even some of the large hour-by-hour programs like DOE-2 are beginning to be available for PC's.) Efforts to integrate both simplified and detailed energy calculations into CAD systems will increase. In parallel, the thrust for more precise simulation of physical processes will continue in such areas as natural convection, moisture and contaminant flow, multi-dimensional conduction, natural ventilation, solar-optical behavior of window shading systems, HVAC system control dynamics, HVAC component performance, and envelope/HVAC systems coupling.

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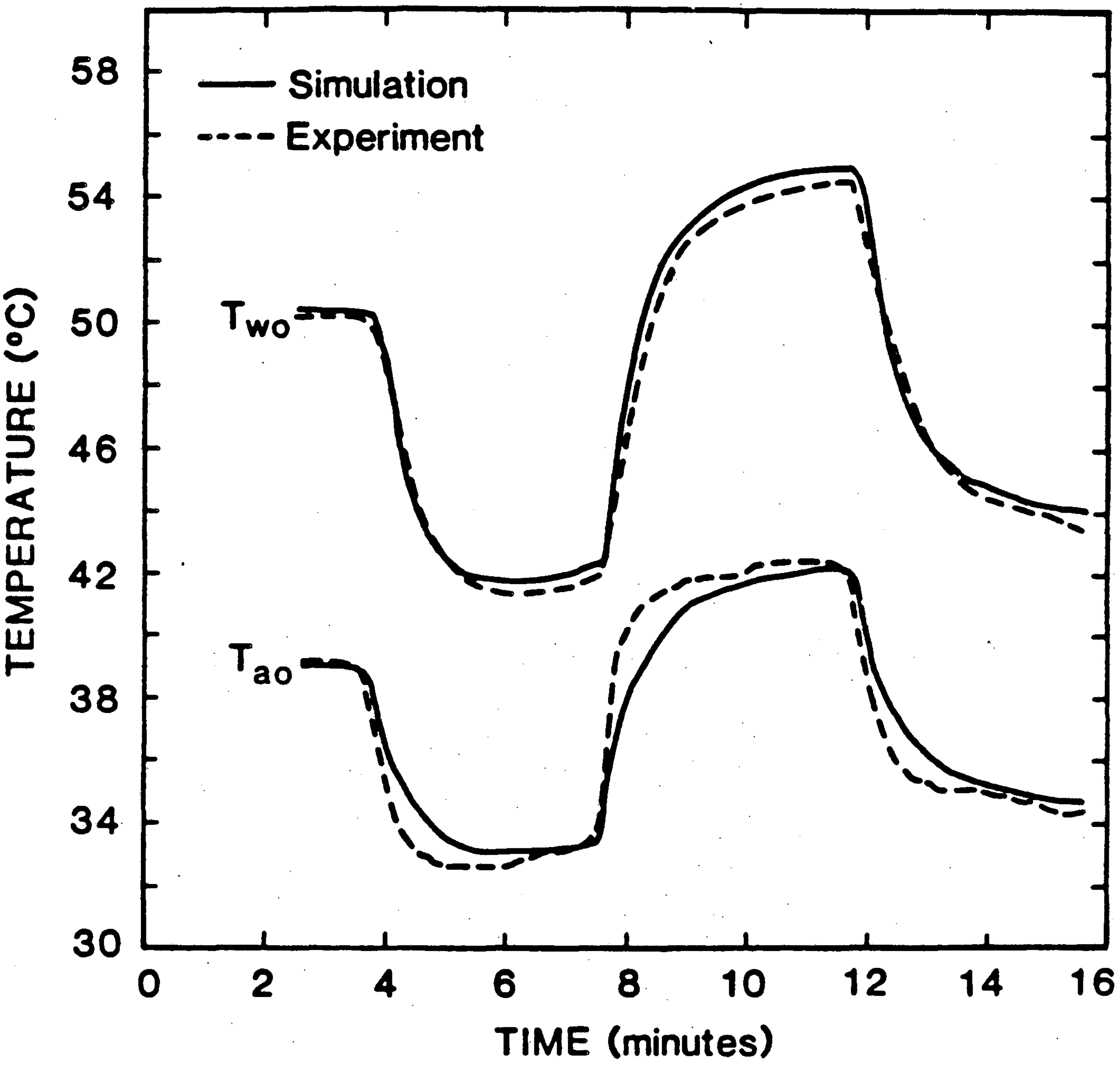

Figure 1 Heating coil response to rapid changes in water inlet temperature: comparison of small-timestep HVACSIM$^+$ predictions and measurements of air and water outlet temperature, T_{ao} and T_{wo}. (From Ref. 3)

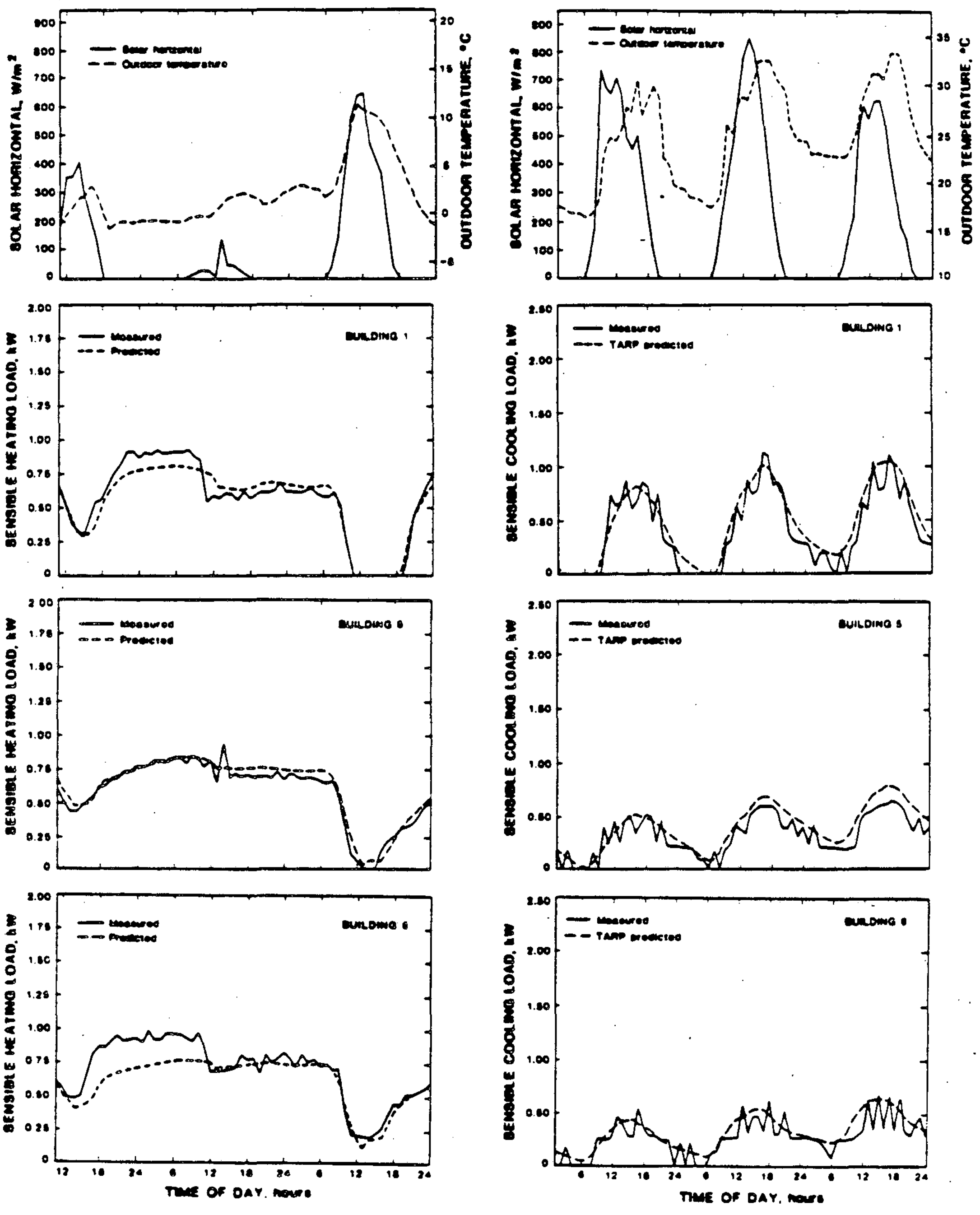

Figure 2 TARP hourly load predictions compared to measurements on three NBS test buildings in Gaithersburg, MD, for a winter test period (left hand plots) and a summer test period (right hand plots). The buildings are identical except for exterior wall construction: Building 1 is insulated wood frame, Building 5 is log, and Building 6 is masonry with exterior insulation. (Results for three other buildings — uninsulated wood frame, uninsulated masonry and masonry with interior insulation — may be found in Ref. 11.)

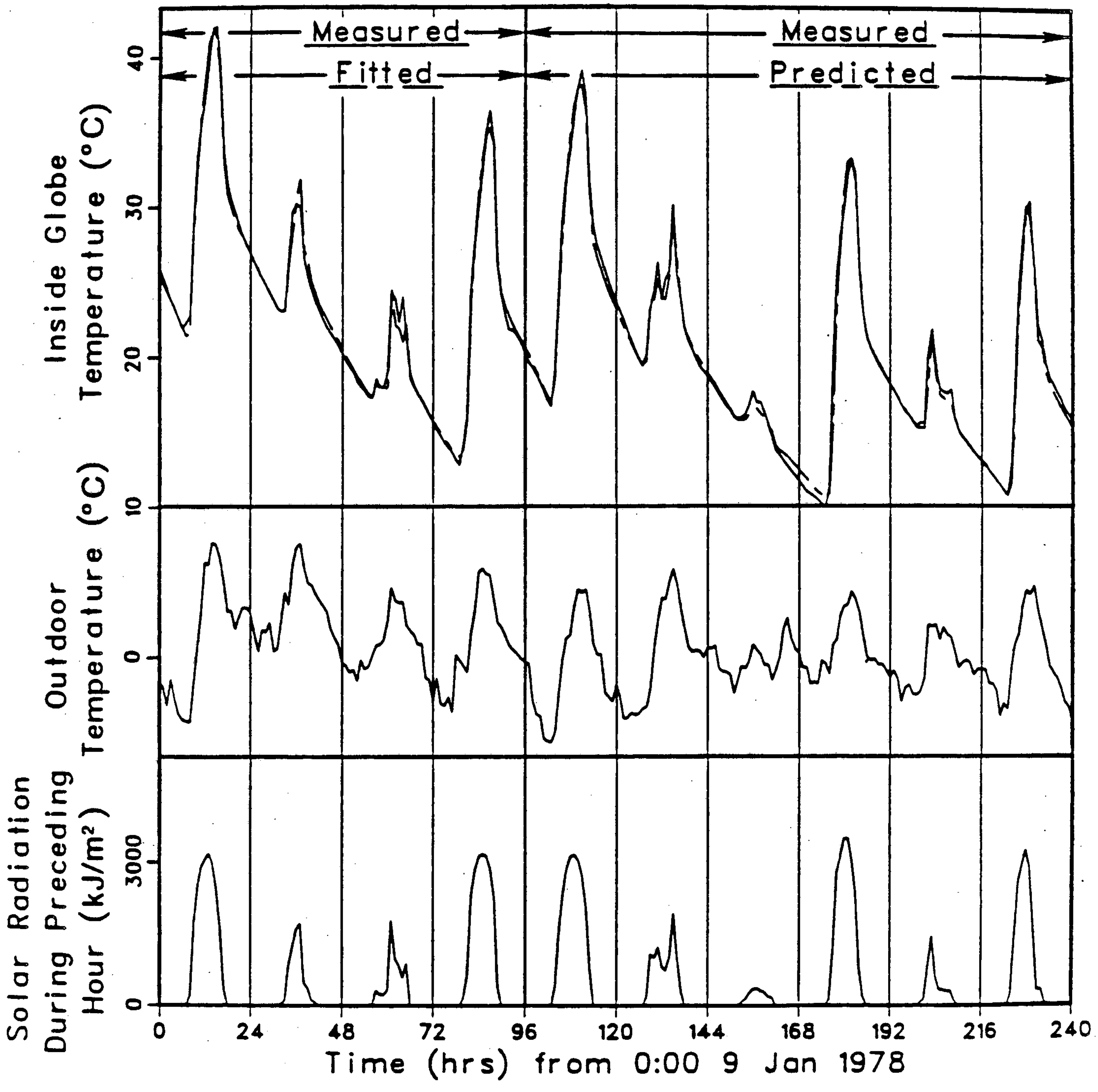

Figure 3 BEVA analysis of the Los Alamos direct gain test cell for a 10-day period in January. A fit to the first four days of measured inside temperature gave system parameters used to predict the following six days. (From Ref. 15)

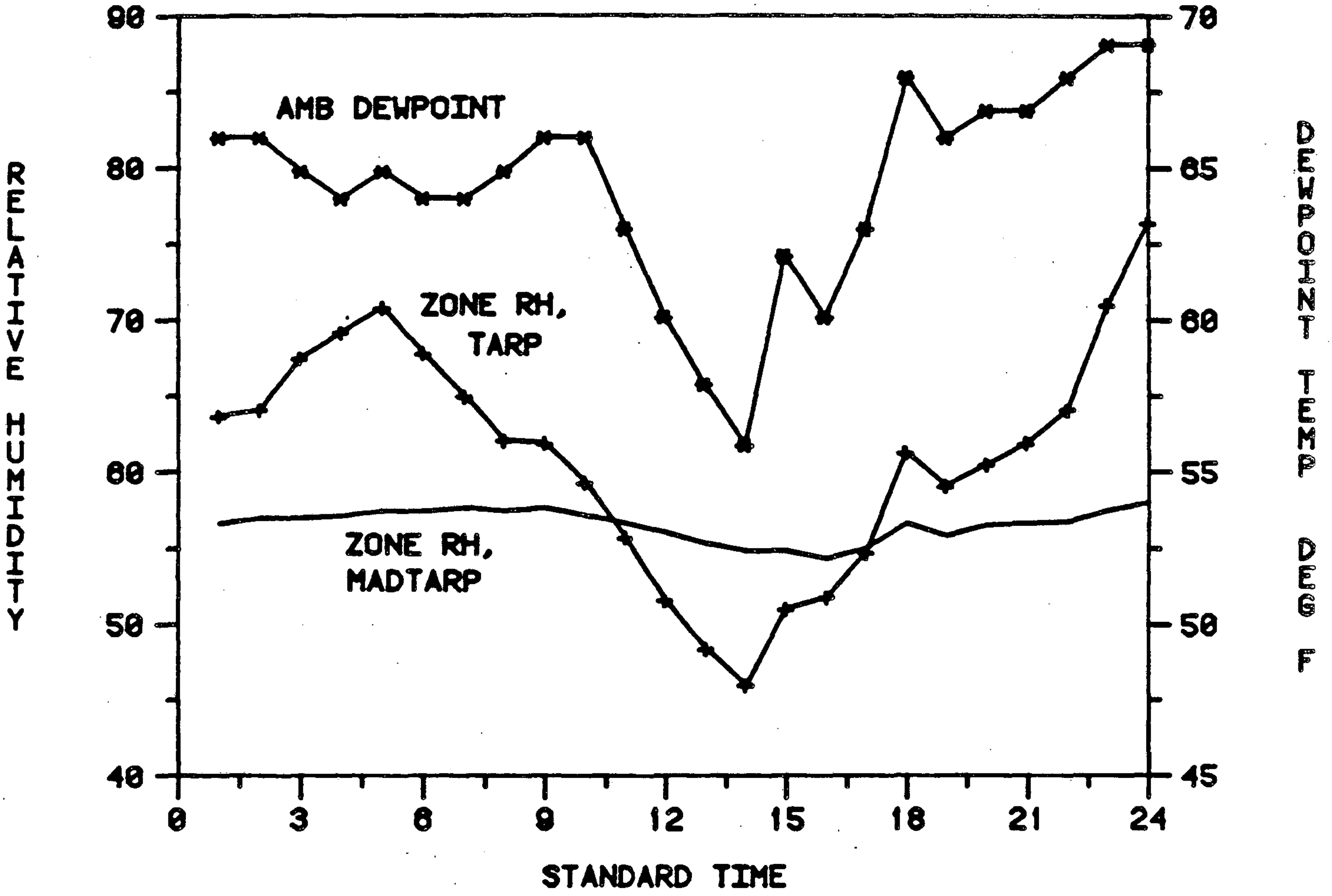

Figure 4 Comparison of room-air relative humidity predictions for TARP (without moisture absorption/desorption) and MADTARP (with moisture absorption/desorption). Results are shown for a typical single-family woodframe house, for a July day in Atlanta, GA. Upper curve is dewpoint temperature of outside air. (From Ref. 18)

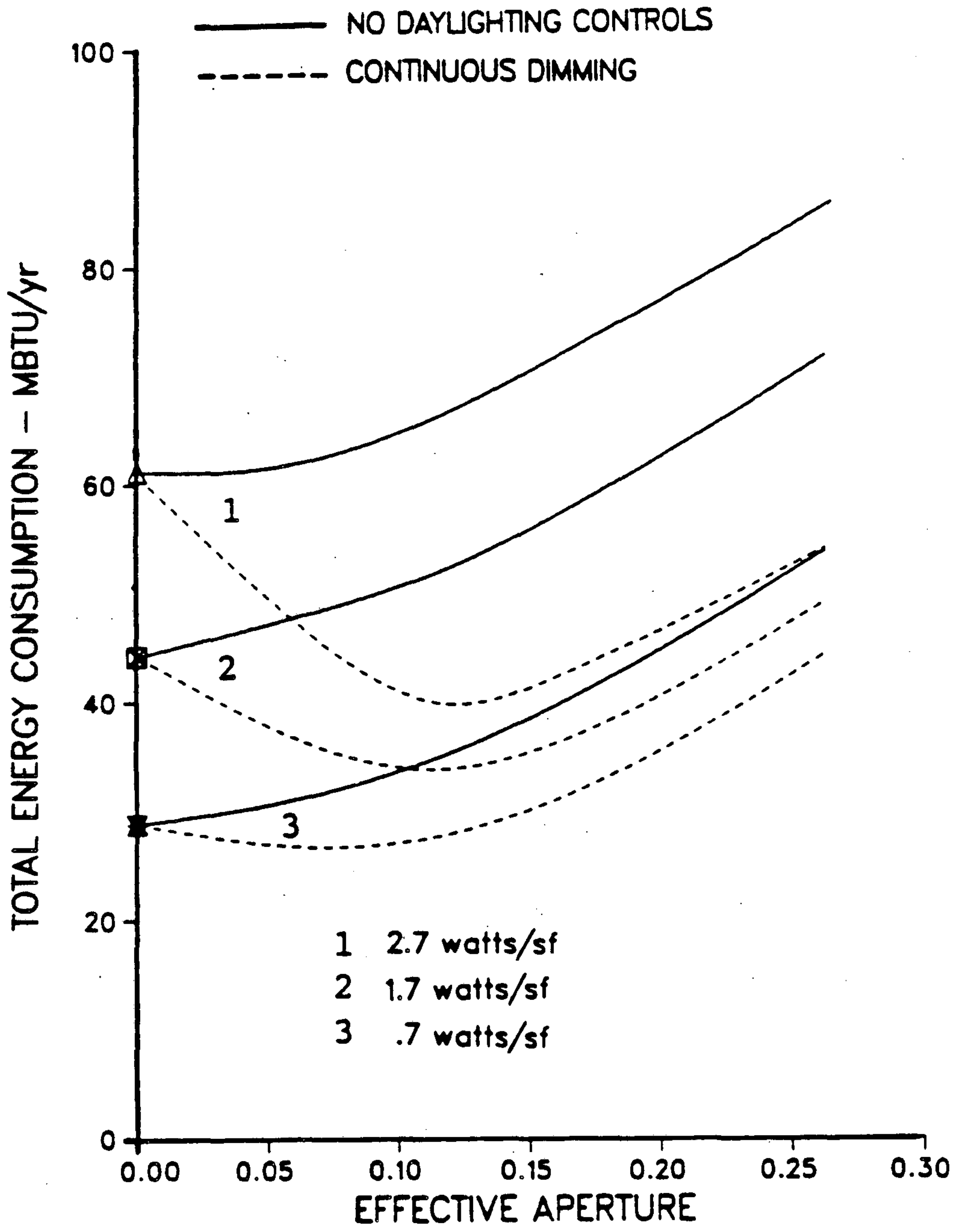

Figure 5 DOE-2 prediction of annual energy use vs. effective aperture (window-to-wall ratio times visible transmittance of glazing) for a south-facing office module in Los Angeles. Results are shown with and without daylighting controls, for three different lighting power densities. As the effective aperture increases, the curves with daylighting controls fall initially due to reduced electric lighting energy, reach a minimum, then rise as the cooling load from solar gain becomes dominant. (From Ref. 25)

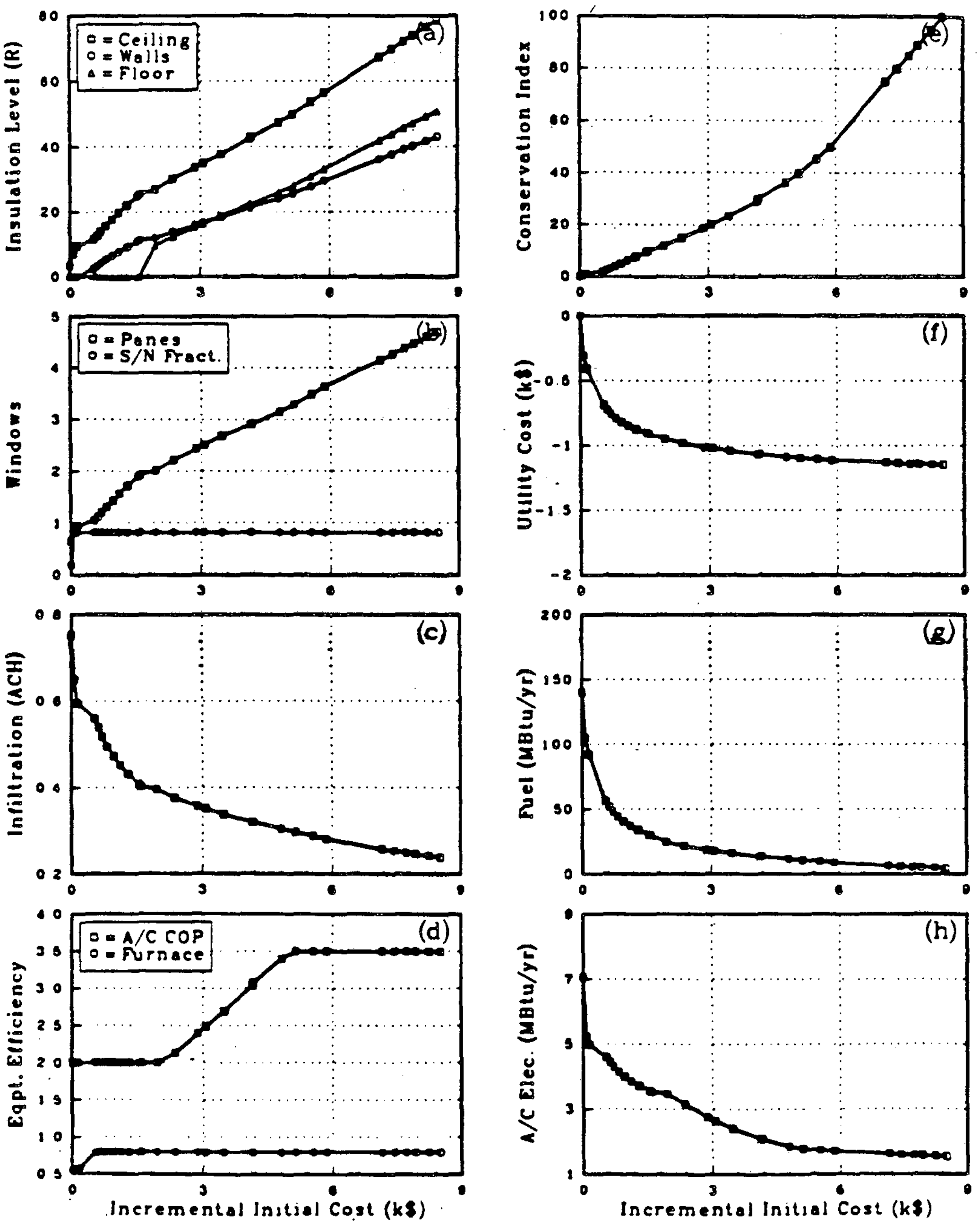

Figure 6 Plots of optimal configurations as a function of the incremental initial costs for a typical residence in New York City. Left column plots (a-d) are optimized building configuration parameters; right column plots (e-h) are selected performance characteristics of the configuration. In (b), "S/N Fract." is the ratio of south to south-plus-north window area. (The total window area was constrained to 15% of the floor area, of which 2% was assigned to the east facade, 2% to the west, and the remainder to the north and south.) "Conservation Index", (e), is a measure of the relative importance of initial cost relative to annual operating cost. (From Ref. 26)